Vortex Pinning and Dynamics in Layered Superconductors with Periodic Pinning Arrays

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We examine vortex dynamics and pinning in layered superconductors using three-dimensional molecular dynamics simulations of magnetically interacting pancake vortices. Our model treats the magnetic interactions of the pancakes exactly, with long-range logarithmic interactions both within and between planes. At the matching field the vortices are aligned with the pinning array. As a function of tilt angle for the pinning arrays a series of commensuration effects occur, seen as peaks in the critical current, due to pancakes finding a favorable alignment.

In superconductors with periodic pinning arrays interesting commensurability effects occur when the periodicity of the vortex lattice matches the periodicity of the pinning lattice. Experiments [1,2] and simulations [3] so far have been done with thin film superconductors where the vortex lattice and pinning can be considered two-dimensional. The case of vortex lattices interacting with a periodic pinning array in a layered 3D superconductor has not been studied. Such a system would correspond to an anisotropic superconductor such as BSCCO with a periodic arrangement of columnar defects. In this system the z-direction becomes important as the applied field or the pinning array is tilted. The dynamical effects of vortices moving in periodic pinning arrays in such a system have not been examined, in particular how the vortex lattice structure of the moving state differs from that of the pinned state. To study vortex pinning and dynamics in layered superconductors, we have developed a simulation containing the correct magnetic interactions between pancakes [4]. This interaction is long range both in and between planes, and is treated using a rapidly converging summation method [5].

The overdamped equation of motion, for $T = 0$, for vortex i is given by $\mathbf{f}_i = \sum_{j=1}^{N_v} \nabla \mathbf{U}(\rho_{i,j}, z_{i,j}) + \mathbf{f}_i^{vp} + \mathbf{f}_d = \mathbf{v}_i$, where N_v is the number of vortices and ρ and z are the distance between pancakes in cylindrical coordinates. The magnetic energy between pancakes is

$$\mathbf{U}(\rho_{i,j}, 0) = 2d\epsilon_0 \left((1 - \frac{d}{2\lambda}) \ln \frac{R}{\rho} + \frac{d}{2\lambda} E_1(\rho) \right)$$

$$\mathbf{U}(\rho_{i,j}, z) = -\frac{d^2\epsilon_0}{\lambda} \left(\exp(-z/\lambda) \ln \frac{R}{\rho} - E_1(R) \right)$$

where $R = \sqrt{z^2 + \rho^2}$, $E_1(x) = \int_\rho^\infty \exp(-x/\lambda)/\rho' d\rho'$ and $\epsilon_0 = \Phi_0^2/(4\pi\xi)^2$. The pinning is placed in a square array of parabolic traps with a radius r_p much smaller than the distance between pins. The location of the pinning sites is the same in every layer corresponding to correlated defects. A driving force f_d is slowly increased and the vortex velocities are measured. Here we consider the first matching field case where the number of vortices N_v equals the number of pinning sites N_p. We conduct a series of simulations in which the pinning sites are tilted at an increasing angle with respect to the z-axis. We will only consider driving that produces vortex motion transverse to the direction of the tilt angle. We examine systems with 8 layers containing 64 vortices and pins in

each layer. Work for larger systems, varied fields and coupling strength will be presented elsewhere [6].

In Fig. 1(a) we present the critical depinning force f_{dp}^c as a function of tilt angle θ. Here f_{dp}^c peaks at $\theta = 0°$ when the pancakes are aligned with pins on all layers. As θ is increased f_{dp}^c drops. For small tilt angles $\theta < 5°$ the vortex lines tilt with the pins. For larger angles the vortex lines realign in the z direction. The depinning force f_{dp}^c will then remain low as only one pancake in the straight vortex line will be sitting at a pinning site. At $\theta = 45°$ f_{dp}^c shows a peak of the same magnitude as the peak at $\theta = 0$. At this tilt angle, and also for any angle satisfying $\theta = \tan^{-1}(n)$ where n is an integer, the pinning sites are again aligned in the z-direction so that a vortex line can be formed that is also aligned in the z-direction with all the pancakes in a single vortex being able to sit in a pinning site. There are also peaks in f_{dp}^c at $\theta = 26.6°$ and $56.3°$. At these angles the pancakes again sit on all the pinning sites. The individual vortex lines now consists of half the number of pancakes as at $\theta = 0.0°$; however, there are now twice as many vortex lines with the pancakes from an individual vortex line being coupled in every other layer. The view from the z-direction as shown in Fig. 1 for these angles indicates that the vortex lattice is now rectangular with twice as many vortex lines as at the other angles. At $\theta = 36.9°$ a smaller peak is observed. The vortex structure at this angle will be presented elsewhere [6].

In (b) and (c) we show the vortex structures for the pinned phase and moving phase for $\theta = 1.5°$ as seen from the z-direction. In (b) the vortices can be seen to stay aligned with the pins. In (c) for $f_d > f_{dp}^c$ the vortices realign with the z-direction. Such a transition from a tilted to straight vortex lattice as a function of drive may be visible with neutron scattering experiments.

We acknowledge helpful discussions with L. N. Bulaevskii, A. Kolton, R.T. Scalettar, and G. T. Zimányi. This work was supported by CLC and CULAR (LANL/UC) and by the Director, Office of Adv. Scientific Comp. Res., Div. of Math., Information and Comp. Sciences, U.S. DoE contract DE-AC03-76SF00098.

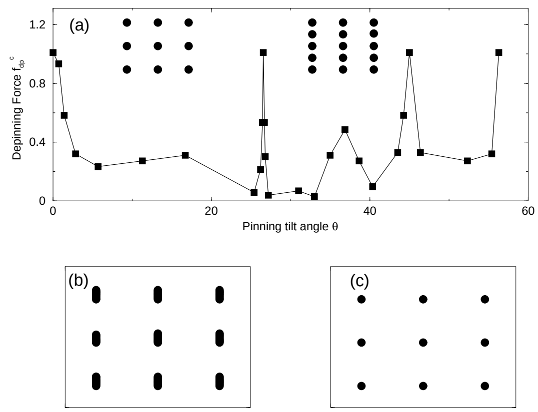

Figure 1. The critical depinning force f_{dp}^c versus the tilt angle θ of the pinning sites. The vortex arrangements as seen from the z-direction are outlined for different tilt angles $\theta = 0$ left and $\theta = 26.6$ right. (b) shows the pinned vortex arrangement for $\theta = 1.5°$ where the vortices stay aligned with the pins. (c) shows the moving vortex state for $\theta = 1.5°$ where the vortices have realigned with the z direction.

REFERENCES

1. M. Baert *et al.*, Phys. Rev. Lett. **74**, 3269 (1995); K. Harada *et al.*, Science **271**, 1393 (1996).
2. J.I. Martín *et al.*, Phys. Rev. Lett. **79**, 1929 (1997); Y. Fasano *et al.*, Phys. Rev. B **60**, R15047 (1999).
3. C. Reichhardt, C.J. Olson and F. Nori, Phys. Rev. B **57**, 7937 (1998).
4. J.R. Clem, Phys. Rev. B **43**, 7837 (1990).
5. N. Grønbech-Jensen, Comp. Phys. Comm. **119**, 115 (1999).
6. C. Reichhardt, C.J. Olson and N. Grønbech-Jensen, to be published.